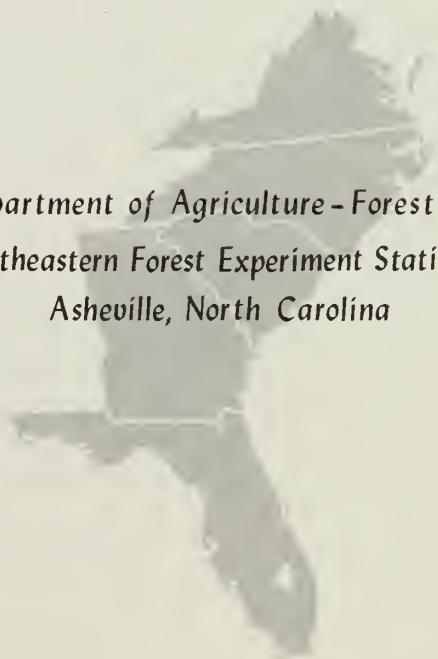



Some Factors Affecting the Moisture Timelags of Woody Materials



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Some Factors Affecting the Moisture Timelags of Woody Materials

by

Ralph M. Nelson, Jr.

Associate Wood Technologist
Southern Forest Fire Laboratory
Macon, Georgia

The primary theoretical tool available for predicting the effects of weather and fuel variables on the drying rates of forest fuels is the well-known theory of diffusion in solids, which has been developed from the classical theory of heat conduction. The applicability of the theory of diffusion to the drying of forest fuels has not been clearly determined. There is little doubt of the existence of limitations in the classical approach to the drying of solids (3), but some question remains concerning the ways in which these limitations affect the usefulness of the equations. Although actual moisture gradients and moisture content-time curves for woody materials often fail to coincide completely with theoretical curves, relationships between the drying rate constant and variables in the theoretical equations may prove to be correct and useful.

The research reported here was carried out to determine the effects of thickness of the sample, air temperature, and air relative humidity on the drying rate constant, and to compare these experimentally determined relationships with the corresponding theoretical relationships.

Wetting (adsorption) rates were not considered. Under similar conditions, the drying of dead forest fuels should follow the same laws as does the drying of woody materials in the laboratory. Comparison of the experimental results of this study with the corresponding theoretical results, therefore, should be immediately useful in determining the applicability of diffusion theory to drying processes in forest fuels.

ELEMENTS OF CLASSICAL DIFFUSION THEORY

The assumption upon which classical diffusion theory is based is that the rate of mass flow per unit area at any point in an isotropic material is proportional to the concentration gradient of diffusing substance at that point. This statement is known as Fick's first law of diffusion and is stated mathematically as

$$F = -D \frac{\partial C}{\partial x} \quad (1)$$

where F is the rate of mass flow per unit area at a point within the material, $\frac{\partial C}{\partial x}$ is the concentration gradient in the direction of flow at the point, and D is a constant of proportionality usually termed the diffusion coefficient. The minus sign is written to indicate that mass flow is in the direction of decreasing concentration.

Equation (1) may be used to derive Fick's second law of diffusion. This law states that for a given direction of diffusion, the rate of change of concentration of the diffusing substance at any point within the material is proportional to the rate of change of the concentration gradient with respect to distance. For simultaneous diffusion in the x , y , and z directions, the mathematical form of Fick's second law is

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left(D \frac{\partial C}{\partial z} \right) \quad (2)$$

where C is concentration of diffusing substance and t is time.

To facilitate integration of equation (2), D is usually regarded as constant, so that for the simple case of drying in one direction, say the x direction, equation (2) reduces to

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad (3)$$

It is generally found that D is not constant but a function of either concentration or time, so that solutions of equation (3) are only approximations of the actual drying behavior. Integrations of equation (3) have been carried out for materials of different shapes drying in response to various combinations of initial and boundary conditions. Mathematical descriptions of the diffusion process have been given by Jost (4), Barrer (1), and Crank (2).

The Timelag Concept

In a recent analysis of the drying process in forest fuels, Byram¹ generalized Fick's first and second laws by postulating the existence of a quantity, g , the gradient of which provides the driving force for the diffusion process in forest fuels. He assumed that g is a function of one or more properties of the moisture in the fuel, such as concentration, C , moisture content, m , or vapor pressure, p . Because the nature of the driving force is not known, Byram considered the following expressions for g : C , m , p , CP , and mP , where P is the saturation vapor pressure of water at the drying temperature. In terms of g , Byram's expressions for equations (1), (2), and (3) are

$$F = -k \frac{\partial g}{\partial x} \quad (1a)$$

¹Byram, George M. An analysis of the drying process in forest fuel material. 1963. (Unpublished report on file at the Southern Forest Fire Laboratory, Southeastern Forest Experiment Station, U.S.D.A. Forest Service, Macon, Georgia.)

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial g}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial g}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial g}{\partial z} \right) \quad (2a)$$

$$\frac{\partial C}{\partial t} = k \frac{\partial^2 g}{\partial x^2} \quad (3a)$$

The quantity, k , is interpreted as a moisture conductivity and corresponds to thermal conductivity in heat transfer. The physical meaning and dimensions of k depend on the choice of g . Byram showed that, in a mathematical sense, no single g function is preferable to any other.

In a physical sense, however, certain choices for g seem preferable to others. Byram chose to work with $g = mP$. His analysis of the drying process on this basis shows that the drying of dead forest fuels in the form of rods, slabs, cylinders, cubes, and spheres should be represented by the equation

$$\frac{\bar{m} - m_e}{m_0 - m_e} = Ke^{-\left(\frac{N^2 k P}{\rho r^2}\right)t} = Ke^{-\left(\frac{N^2 D}{r^2}\right)t} \quad (4)$$

except for small values of time. In equation (4)

\bar{m} = average moisture content of the fuel

m_e = equilibrium moisture content

m_0 = initial moisture content

K = a dimensionless constant which depends on fuel shape

e = base of Napierian logarithms, 2.718

N = a dimensionless number, the value of which depends on k , r , and the surface moisture transfer coefficient, h

k = fuel moisture conductivity, in sec.

P = saturation vapor pressure of water at the drying temperature, in $\frac{\text{dynes}}{\text{cm.}^2}$

ρ = swollen-volume fuel density, in $\frac{\text{gm.}}{\text{cm.}^3}$

r = half-thickness or radius of the fuel, in cm.

t = time, in sec.

D = diffusion coefficient (or moisture diffusivity) of the fuel, in $\frac{\text{cm.}^2}{\text{sec.}}$

All moisture contents are expressed as fractions of the oven-dry weight of the fuel. Equation (4) is a solution of equation (3a) and is based on several assumptions: (a) the fuel is an isotropic, nonshrinking material; (b) moisture conductivity, k , and diffusion coefficient, D , are constants in any single drying process; (c) a uniform distribution of moisture exists in the fuel prior to drying; (d) diffusion occurs only in the r direction; (e) temperature gradients do not exist in the fuel during drying; (f) fuel temperature is the same as ambient air temperature; and (g) evaporation of moisture occurs only at the fuel surface. Although few of these assumptions are valid for actual drying processes, equation (4) may be a sufficiently good description of the drying process to predict correctly how the variables involved affect the drying rate.

The timelag "constant," or timelag, is a parameter which is characteristic of all physical and chemical processes that occur at an exponentially decreasing rate. When written in terms of the timelag, τ , equation (4) becomes

$$\frac{\bar{m} - m_e}{m_o - m_e} = E = Ke^{-\frac{t}{\tau}} \quad (5)$$

where

$$\tau = \frac{\rho r^2}{N^2 k P} = \frac{r^2}{N^2 D} \quad (6)$$

and E is the fraction of total evaporable moisture remaining in the fuel at time t . A plot of E versus time on semilogarithmic graph paper will be linear if equation (5) is obeyed. The slope of such a plot, derived from differentiation of the logarithmic form of equation (5), is

$$\frac{d}{dt} (\ln E) = -\frac{1}{\tau} \quad (7)$$

The constant K is the value of E at which the extended linear portion of the plot (extrapolated to $t = 0$) intersects the E -axis, and its theoretical value depends only on the shape of the drying fuel. From experimentation, on the other hand, it is found that K is not determined solely by the shape of the fuel; other unknown factors affect its magnitude. The countless combinations of fuels and drying conditions found in the forest make evaluation of K for each fuel and drying condition an impossible task. However, experimental values of K for uniform samples are usually close to unity. For this reason the timelag concept, as applied to the drying of forest fuels, is based on the assumption that $K = 1$. On this basis, the moisture timelag is defined as the time required for the difference between the average and equilibrium moisture contents, $(\bar{m} - m_e)$, to decrease to the value $\frac{1}{e} (m_o - m_e)$ under constant drying conditions. Thus, when $t = \tau$ in equation (5), the fraction of evaporable moisture remaining in the fuel is $\frac{1}{e}$, or 0.368.

The timelag cannot be calculated directly from equation (6) because values of N^2 , k , and D are not known. However, the timelag may be determined experimentally by application of equation (7) to a semilogarithmic plot of the drying data in which E is shown as a function of t . An alternative method of determining τ from the same plot is to draw a line through the point $E = 1$, $t = 0$, with a slope parallel to the linear portion of the curve; timelag τ is the value of t for which $E = 0.368$. Construction of a line parallel to the linear portion of the data and passing through the given point is necessary in order to graphically correct K to a value of unity.

Relationships Between the Timelag and Certain Drying Variables

Among the many factors which influence the drying of forest fuels are fuel thickness, air temperature, fuel density, relative humidity, wind-speed, and initial moisture content. Relationships between the timelag and some of these factors may be predicted theoretically by means of equation (6). For example, the timelag should be proportional to r^2 , according to equation (6). Byram (see footnote 1) has shown that this type of behavior is to be expected when r is large and the rate of moisture loss is limited by the rate of internal moisture flow, that is, by the internal resistance. Under these conditions, N^2 approaches the value $\frac{\pi^2}{4}$. However, when r is small, the rate of moisture loss is determined primarily by the surface resistance. In this case, N^2 in equation (6) approaches the value $\frac{hr}{k}$, where h is the coefficient of moisture transfer at the fuel surface. Drying under these conditions occurs with a relatively small moisture gradient through the fuel, and the timelag in equation (6) becomes

$$\tau = \frac{\rho r^2}{N^2 k P} = \left(\frac{k}{hr} \right) \left(\frac{\rho r^2}{k P} \right) = \frac{\rho r}{h P} \quad (8)$$

Thus, diffusion theory predicts that a log-log plot of τ against r for constant-density fuels of varying thicknesses which are drying in constant-temperature surroundings should have a slope of 2.0 except when r has very small values, in which case a slope of unity should be approached.

The effect of air temperature on τ is evident from its effect on the saturation vapor pressure of water, P . According to equation (6), a log-log plot of τ against $\frac{1}{P}$ should have a slope of unity for fuels of equal thickness and density which are drying in surroundings of different temperatures.

The effect of fuel density on the timelag should result in a log-log plot of τ against ρ with a slope of unity, according to equation (6).

Variables such as relative humidity, windspeed, and initial moisture content do not appear in equations (6) and (8). Thus, from the standpoint of the theory upon which the equations are based, these variables have no effect on the magnitude of the timelag.

EXPERIMENTAL PROCEDURE

The purpose of the experimental work was (1) to determine the effects of thickness of the sample, air temperature, and air relative humidity on the timelag constants of several types of woody materials and (2) to compare these effects with the corresponding effects predicted from diffusion theory in the previous section. Study of the effects of sample density and windspeed was omitted. The effect of initial moisture content on the magnitude of the timelag was studied briefly with one of the experimental materials, but was not of major interest.

Drying measurements were made on layers of white fir, Abies concolor (Gord. and Glend.) Lindl., sawdust which had a swollen-volume bulk density of about 0.10 gm./cm.³, on square rods sawn from white fir lumber which had a density of 0.350 gm./cm.³, and on slabs built up from individual sheets of thin copy paper which had a density of 1.0 gm./cm.³. Most of the samples were dried from an initial moisture content of approximately 100 percent so that the effect of a high initial moisture content on the shapes of the moisture content-time curves could be studied. All measurements were made inside a walk-in cabinet in which dry bulb temperatures and relative humidity were controlled. The average range of variation of the dry and wet bulb temperatures was about 4° F.; the maximum observed variation was 5.7° F. These temperature variations caused a maximum oscillation in relative humidity of about ± 5 percent from the mean values. The sawdust layers were dried in aluminum pans; the square wooden rods and paper slabs were dried on hardware cloth supported above a table so that air could circulate freely on all sides. Weight loss measurements were accurate to ± 0.5 percent. When the moisture content of each sample had reached equilibrium with conditions in the cabinet, the sample was oven-dried at 105° C. and its oven-dry weight determined.

The effect of thickness on the timelags of samples of sawdust, wood, and paper, each held at approximately 81° F. and 36 percent relative humidity, was studied. Determinations on the sawdust were made on layers which were of the following four wet thicknesses--0.9, 1.5, 2.8, and 5.5 centimeters. Samples at each thickness were dried from initial moisture contents of 104, 58, and 34 percent. All layers were dried in a constant wind of 2.2 m.p.h. (These samples were dried before wind was omitted as an experimental variable.)

The effect of thickness on the timelags of the wooden rods was evaluated under conditions in which the movement of air was caused only by circulation in the humidity cabinet itself--conditions approaching free convection. Rods of the following thicknesses, based on air-dry thickness

at 11 percent moisture content, were tested: 0.14, .33, .64, 1.3, and 2.6 centimeters. The rods were dried from initial moisture contents near 100 percent.

The effect of thickness on the timelags of the paper slabs was measured under conditions similar to those used for the square rods. The wet slabs were approximately 0.013, .025, .051, .102, and .203 centimeter thick. Measured values of initial and equilibrium moisture contents are in slight error because of decomposition of the paper during oven drying. However, the weight loss-time data are accurate because they did not depend on determination of the starting and final moisture content values.

The effect of temperature on the timelag was evaluated for four layers of sawdust 0.80 centimeter thick and for four square wooden rods 0.64 centimeter thick. Tests were run at temperatures of 60, 80, 90, and 100° F., with the samples initially in thermal equilibrium at the test temperatures. Relative humidity was held at about 39 percent, and all samples were dried in free-convection surroundings. The initial moisture content of the sawdust samples averaged 92 percent with variations of only 3 percent. The wood samples, however, varied from 55 to 88 percent in initial moisture content because of moisture loss during storage at the test temperature. This loss may have resulted from an evaporation-condensation process caused by small air temperature fluctuations within the storage cabinet.

The effect of relative humidity on the timelag of four layers of sawdust 0.80 centimeter thick and five 1.27-centimeter square wooden rods, each held at a temperature of about 80° F., was studied. Relative humidity values for drying of the four sawdust layers were 69, 50, 36, and 21 percent; corresponding values for the five wooden rods were 83, 60, 46, 30, and 18 percent. Samples within each fuel type were of nearly equal densities and were dried under free-convection conditions. Initial moisture contents of both the sawdust and wood averaged 93 percent.

EXPERIMENTAL RESULTS

The weight-time data for all samples were plotted on semilogarithmic graph paper so that timelags could be determined in accordance with equation (7). Even for large times, the experimental curves did not take the general form predicted by equation (5), although certain portions of the curves were linear in accordance with the theory (fig. 1). In most cases, the semilogarithmic plots could be separated into three distinct regions. The region corresponding to the smallest times was linear; this portion of the curve usually began at the point at which drying started and ended at a point which represented a moisture change between 30 and 80 percent of the total change. The second portion of the curve was curvilinear, extending from the point at which the initial linear portion stopped to a point at which the sample had lost 80 to 90 percent of its evaporable water. The third region of the curves was usually linear, but with a slope different from that of the first region. Because most of the samples gave semilogarithmic plots with two linear regions, they were considered to

exhibit two timelags. Thus, the effects of thickness, air temperature, and relative humidity were evaluated for two timelags, τ_1 and τ_2 . The symbol τ_1 refers to the linear region associated with the initial stage of drying; the symbol τ_2 refers to the linear region associated with the final stage of drying.

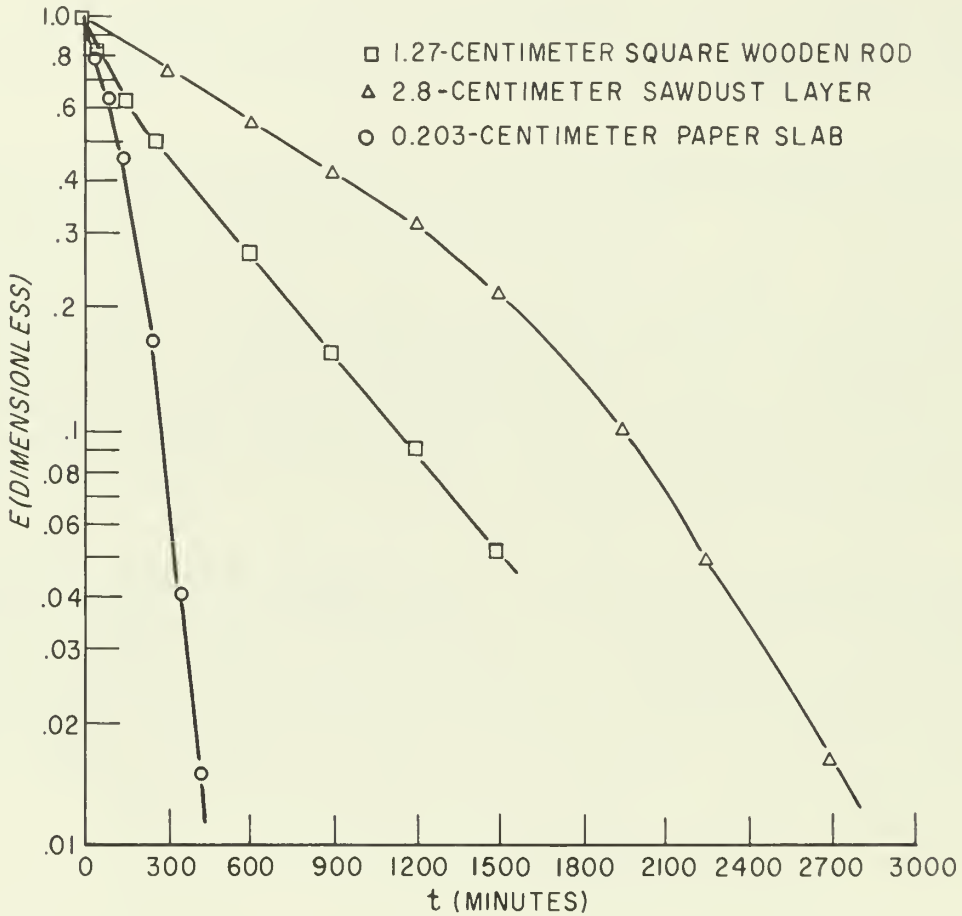


Figure 1.--Typical drying curves for sawdust layers, square wooden rods, and paper slabs dried at 81° F. and 36 percent relative humidity. The fraction of total evaporable moisture in the sample, E , is plotted against time.

The Effect of Thickness

The effects of thickness on τ_1 and τ_2 for the three types of samples are shown in figures 2, 3, and 4. For sawdust (fig. 2), τ_1 is dependent on initial moisture content and thickness, whereas τ_2 is dependent only on thickness, provided that the initial moisture content exceeds 34 percent. The 34-percent samples exhibited only one timelag because of their low initial moisture contents. The slopes of the plots for both τ_1 and τ_2 are 1.85. Although this value is slightly smaller than the

theoretical value of 2.0, it agrees well with the value of 1.80 found by Byram (see footnote 1) for similar drying experiments with sawdust. The reason for this slight deviation from theory is not clear.

Figure 3 shows τ_1 and τ_2 plotted against r for drying of the square wooden rods. Initial moisture contents of all samples but the 2.56-centimeter rod were close to 100 percent; its initial moisture content was 73 percent and was not uniformly distributed. The slope of the line is 2.0, which is in agreement with the theoretical value.

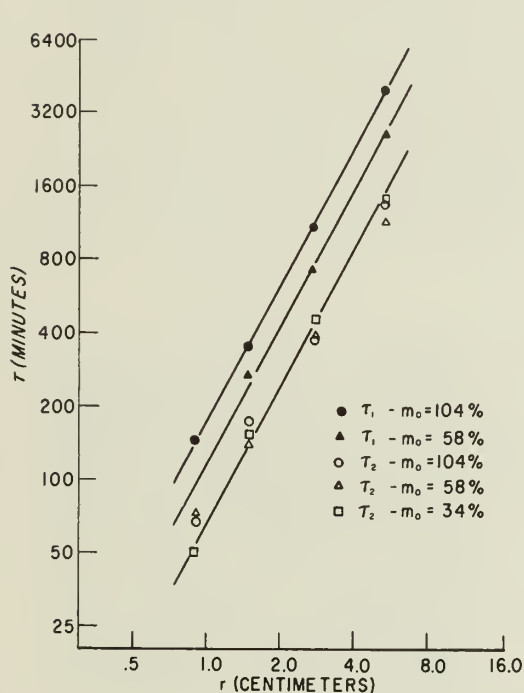


Figure 2.--The effect of thickness on timelags τ_1 and τ_2 of sawdust layers dried at 81° F. and 36 percent relative humidity. The layers were dried from three different initial moisture contents to equilibrium moisture contents of about 10 percent.

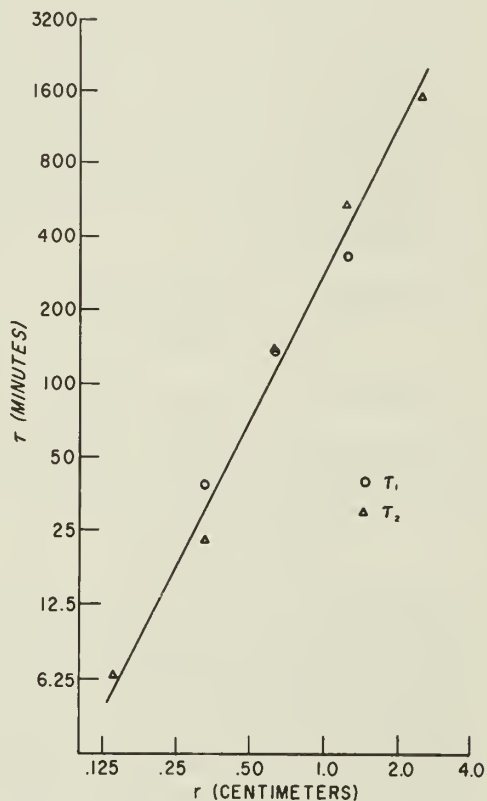


Figure 3.--The effect of thickness on timelags τ_1 and τ_2 of square wooden rods dried at 81° F. and 36 percent relative humidity. The rods were dried from approximately 100 percent moisture content to equilibrium moisture contents of about 10 percent.

The effect of thickness on the timelags of the paper slabs is shown in figure 4. As r increases, the $\tau_1 - r$ curve reaches a slope of 1.27, whereas the $\tau_2 - r$ curve reaches a slope of 2.0. According to diffusion theory, the $\tau_1 - r$ curve should apply when resistance to moisture transfer from the sample surface is large compared with the resistance to internal moisture transfer. In this case, τ_1 should be linear against r with a slope of unity.

Both timelags τ_1 and τ_2 show a tendency to become independent of thickness at values of r in the neighborhood of 0.02 centimeter. However, this observation is based on very limited data near the end of the curves in figure 4. Theoretically, the timelag cannot become independent of thickness. On the other hand, mass drying rates (grams of water lost per unit time) can demonstrate this behavior if the drying process becomes independent of the sample properties. The data for small r values suggested that a mechanism other than diffusion may have been controlling the drying process in the two thinnest samples. Therefore, mass drying rates were calculated for the samples and plotted as functions of the variable E . The drying rates for both samples were nearly equal at equal values of E during the entire drying process and were constant during the first half of the total change in moisture content. Thus, constant-rate drying occurred, indicating that the rate of drying depended upon external conditions rather than upon physical properties of the samples. According to Hougen et al. (3), drying of paper pulp from moisture contents above the fiber saturation point results from capillarity rather than diffusion.

The Effect of Temperature

A dimensionless plot of the timelags τ_1 and τ_2 against the reciprocal of the saturation vapor pressure, $\frac{1}{P}$, is given for both the sawdust layers and the square wooden rods in figure 5. The measured τ_1 values for the wood samples were scattered--probably because of variability in their initial moisture contents. Therefore, on the assumption that time-lag τ_1 varies directly as $(m_0 - m_e)^{\frac{1}{2}}$, a correction of these measured values to a constant initial moisture content of 55 percent was made (see dashed curve in fig. 5). This assumption is based on the meager data in figure 2 and should be verified with more extensive tests. The values shown for sawdust (fig. 5) are actual values; they resulted in a curved line, similar to the curve for corrected values of the wood samples, indicating that the effect of temperature on τ_1 at temperatures near 100° F. may not be in accordance with theoretical predictions. Preliminary temperature measurements on sawdust layers of 100 percent moisture content which were drying at 80° F. and about 30 percent relative humidity indicate that the temperature within the layer drops about 10° F. during the early stages of drying. Increased significance of this cooling effect at temperatures of 90° and 100° F. could account for curvilinearity in the data, but such is not known definitely to be the case. The τ_2 values for both wood and sawdust lie on a straight line with a slope of unity. (Two of the values for wood were not obtainable because of nonlinearity of the data during the late stages of drying.) The results indicate close agreement between the theoretical and experimental relationships in the temperature range from 60° to 100° F.

Similar results have been observed by Stamm and Wilkinson (6). They found that, for temperatures up to about 100° C., the diffusion coefficients for fiberboard which was dried from near the fiber saturation point increased with temperature in proportion to the saturation vapor pressure of water.

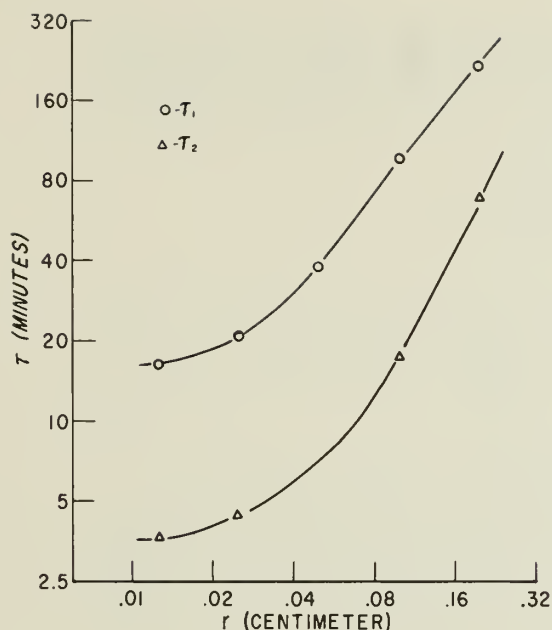


Figure 4.--The effect of thickness on timelags τ_1 and τ_2 of paper slabs dried at 81° F. and 36 per cent relative humidity. The slabs were dried from moisture contents in the neighborhood of 130 percent to equilibrium moisture contents of about 10 percent. Initial and equilibrium moisture contents are approximate because of slight decomposition during overdrying. (The τ_2 value at $r = 0.051$ centimeter is missing because the watch stopped during the measurements.)

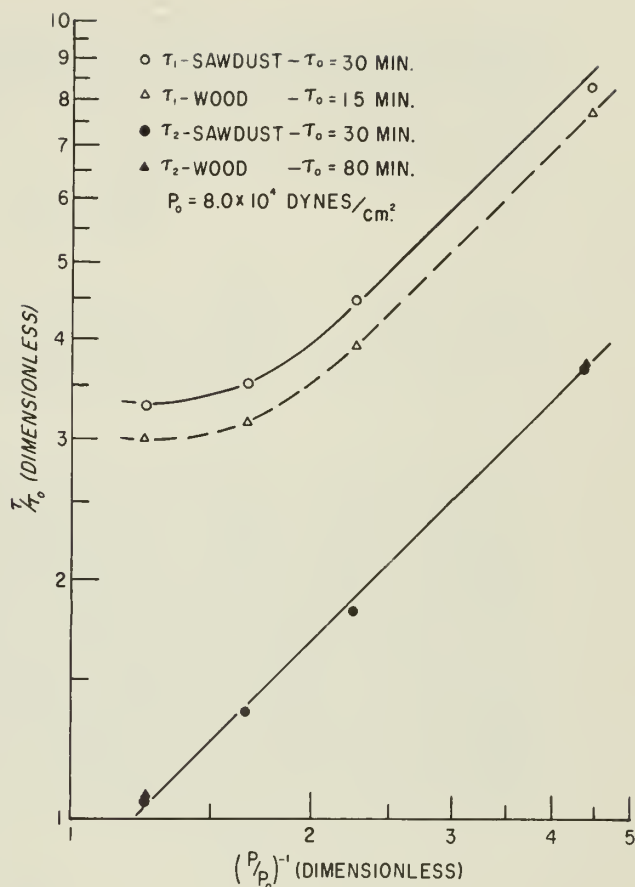


Figure 5.--The effect of temperature on the timelags τ_1 and τ_2 of sawdust layers 0.80 centimeter thick and wooden rods 0.64 centimeter square. The samples were dried at a relative humidity of 39 percent to equilibrium moisture contents of about 10 percent. The initial moisture content of the sawdust layers was 92 percent, and that of the wooden rods was 55 percent. Temperatures ranged from 60° to 100° F. (The terms τ_0 and P_0 are convenient constants which were used so that all curves could be shown on one graph.)

The Effect of Relative Humidity

In experiments on the effect of relative humidity, timelags τ_1 and τ_2 were observed for all sawdust samples but for only three of the wood samples. Several trial plots were made of the experimental timelags as functions of relative humidity. Both τ_1 and τ_2 were best correlated with relative humidity by the equation

$$\tau = C \left(\frac{100}{100 - H} \right) \quad (9)$$

where H is relative humidity in percent and C , a constant with dimensions of time, represents the value of τ when $H = 0$. A log-log plot of

the experimental data is shown in figure 6. The slope of each line is unity. Thus, the data indicate that the timelag is not independent of relative humidity as predicted by equation (6). Further investigation of the effect of relative humidity on the timelag of a number of fuels is needed to verify and extend the data in figure 6.

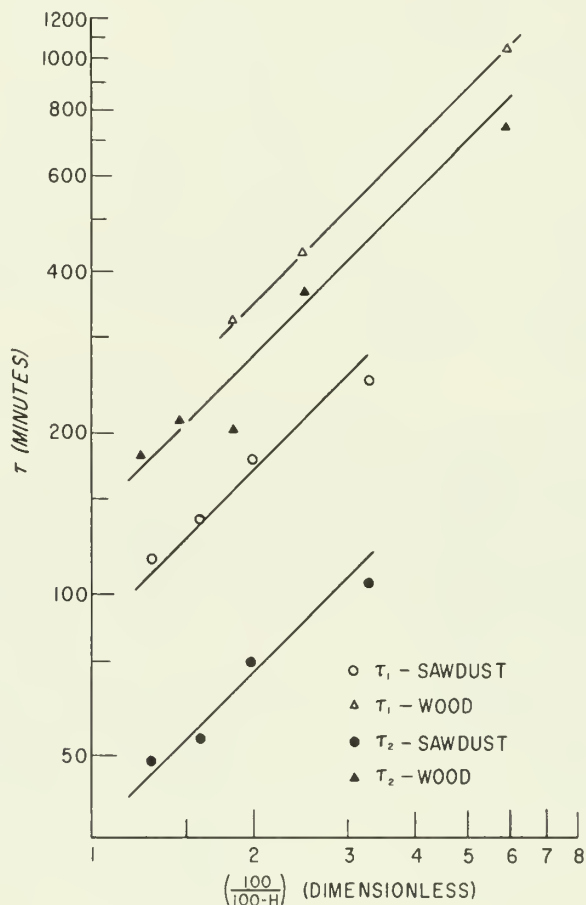


Figure 6. --The effect of relative humidity on the timelags of sawdust layers 0.8 centimeter thick and wooden rods 1.27 centimeters square. The samples were dried at 80° F. from initial moisture contents of about 93 percent.

Knowledge of the effect of relative humidity on the timelag is important from a practical standpoint because development of the National Fire Danger Rating System requires a method of correcting drying rates to standard drying conditions of 80° F. and 20 percent relative humidity. The method of correction was developed by Byram (see footnote 1), who used the assumption that drying of forest fuels occurs in response to a vapor pressure gradient within the fuel. He derived the drying rate ratio, R , for correcting a drying rate observed at temperature T' and relative humidity H' to standard temperature T and standard relative humidity H .

According to Byram, the drying rate ratio for fuels drying from initial moisture contents of at least 20 percent may be calculated approximately from the equation

$$R = \frac{\frac{dM}{dt}}{\frac{dM'}{dt}} = \frac{(100 - H)P}{(100 - H')P'} \quad (10)$$

where P' and P are saturation vapor pressures of water at temperatures T' and T , and $\frac{dM'}{dt}$ and $\frac{dM}{dt}$ are mass drying rates evaluated when $t = \tau'$ and $t = \tau$.

The experimental results indicate that an equation similar to equation (10) may be used to correct any observed timelag τ' to a value τ which corresponds to standard drying conditions. We define a timelag ratio R_τ as the ratio of the timelag for a fuel drying under standard conditions to the timelag for the same fuel drying under conditions other than standard. If temperature and relative humidity are considered to be the only environmental variables affecting the timelag, then the empirical relationships in figure 5 and figure 6 may be combined into a single expression which gives the effects of temperature and relative humidity on the timelag. From figure 5, we have the relation (for temperatures below about 95° F.)

$$\tau \propto \frac{1}{P}$$

and from figure 6, the effect of relative humidity on the timelag is

$$\tau \propto \left(\frac{100}{100 - H} \right)$$

We can combine these two expressions into

$$\tau \propto \left(\frac{100}{100 - H} \right) \frac{1}{P}$$

which may be rewritten as

$$\tau = A \left(\frac{100}{100 - H} \right) \frac{1}{P}$$

where A is a constant. If this equation is valid for all values of H and P normally present in the forest, then the timelag of a fuel drying under conditions which differ from standard conditions is related to the timelag for standard conditions by the timelag ratio

$$R_\tau = \frac{\tau}{\tau'} = \frac{(100 - H')P'}{(100 - H)P} \quad (11)$$

where primed quantities refer to actual drying conditions and unprimed quantities refer to standard conditions. Equations (10) and (11) show that the timelag ratio, R_T , is the reciprocal of Byram's drying rate ratio, R .

DISCUSSION OF RESULTS

The experimental results indicate that woody materials with initial moisture contents greater than the fiber saturation point often dry in two or more stages, with different timelag constants associated with each stage. The appearance of two drying stages may not be of great significance from a practical standpoint because much more moisture is usually lost during the first stage than during the second stage. However, evidence of a more serious limitation is given in figure 2, in which the magnitude of the timelag appears to depend on initial moisture content of the drying material. The practical significance of this effect is not clear. In the field, the effect may be reduced considerably by the presence of other variables, such as solar radiation, wind movement, and nonuniformity of fuel. On the other hand, under certain environmental conditions the time-lags of actual fuels may be affected to about the same extent as were the timelags of the sawdust layers depicted in figure 2. If so, the effect is of considerable importance. For example, if the timelag of a 2-inch layer of fuel material is measured experimentally at a moisture content of 34 percent and if drying of the layer occurs after a rain which has raised the fuel moisture to about 60 percent, then, according to figure 2, use of the measured 34-percent value for the timelag at 60-percent moisture will result in an error of about 43 percent.

The effect of initial moisture content should be most significant during early stages of drying when the materials contain considerable free water. The controlling mechanism during these stages may be either moisture diffusion, heat diffusion, capillarity, or some combination of these factors; its appearance is probably determined by initial moisture content, thickness and nature of the material, and the drying conditions. In the later stages of drying, when much of the free water has been lost, or for initial moisture contents below the fiber saturation point, the controlling mechanism is probably a combination of bound water and water vapor diffusion, as is discussed for the case of wood drying by Stamm and Nelson (5). The relative proportion of each type of diffusion is determined primarily by the internal structure of the material.

CONCLUSIONS

Diffusion theory, in spite of limitations in its description of drying processes in woody materials, is useful for predicting the effects of certain fuel and weather variables on timelag constants of sawdust layers, square wooden rods, and paper slabs. The drying of these materials from moisture contents of 60 percent or greater often occurs in two or more stages, with the occurrence of more than one stage apparently depending on the initial moisture content and the thickness of the drying material.

Theoretical relationships between the timelag and the variables studied are generally applicable to both the initial and final stages of drying even though different timelags are usually associated with each stage, and it is questionable whether simple moisture diffusion occurs during the initial drying stage.

Final-stage timelags of the experimental materials discussed in this report are approximately proportional to the square of sample thickness, provided this thickness exceeds 0.9 centimeter for sawdust layers, 0.14 centimeter for square wooden rods, and 0.10 centimeter for paper slabs. Initial-stage timelags of sawdust and wood are affected by sample thickness in the same way; however, in paper slabs less than 0.2 centimeter thick, the observed initial timelag becomes approximately proportional to the first power of thickness, as predicted for thin materials by diffusion theory. Thus, diffusion theory provides considerable insight into drying processes in thin materials. In extremely thin materials, such as single and double sheets of paper, the drying process is not controlled by diffusion; and the mass drying rates become independent of thickness.

The effect of temperature on the final-stage timelags of wood and sawdust can be predicted by diffusion theory in the temperature range from 60° to 100° F. These timelags are inversely proportional to the saturation vapor pressure of water at the drying temperature. A similar temperature effect occurs for initial-stage timelags up to a temperature of at least 90° F.

The effect of relative humidity on the timelags of the experimental materials in this study was not correctly predicted by the diffusion theory. For sawdust layers and wooden rods, the timelag observed for drying in percent relative humidity H is proportional to the quantity $\left(\frac{100}{100 - H} \right)$.

As this work has shown that the drying process in woody materials may consist of two or more stages, there is now a need to know the range of fuel and weather variables for the different stages and to determine their significance in fire danger measurement. Another research need is study of the effects of size, density, and initial moisture content on timelags of materials dried in atmospheres of oscillating temperature and relative humidity. Research on these two problems should be helpful in successful application of the timelag concept to moisture changes in forest fuels.

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